LCA Methodology

A Structured Framework and Language for Scenario-Based Life Cycle Assessment

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Abstract. It is common to have numerous alternatives and conditions that remain uncertain, but these need to be assessed in decision-making processes. Investigators introduce decision-makers' anticipations and assumptions into analysis when building strategies as a form of scenario. In such a way, scenario analysis is often used as a powerful vehicle for decision making. While a number of LCA case studies dealing with scenarios have been performed, structured frameworks integrating LCA with scenario analysis methodologies have not yet been established. In this paper, we first propose a general framework for scenario-based LCA. The framework provides retrospective and prospective studies with a clear structure. The most important characteristic of the structure is the recognition and separation of three modeling processes, lifecycle modeling, scenario modeling, and valuation modeling, to aim at an increase in reviewability of the entire study and reusability of the constructed models. Next, we introduce a tool, termed lifecycle modeling language (LCML), developed for modeling lifecycle systems and valuation procedures with its relevant scenarios within the proposed framework. LCML facilitates accumulating knowledge obtained from scenario-based LCA studies, by reusing the constructed models, or by applying the same patterns identified from the LCML description, and contributes to reducing the time and efforts needed for an investigation. An illustrative example is presented to show the functionality of LCML.

Keywords: Accumulation of knowledge; design pattern; Java; lifecycle model; lifecycle modeling language (LCML); reusability; reviewability; scenario-based LCA; scenario development; scenario model; XML

1 Introduction

There are various decision making situations where lifecycle thinking is required. Lifecycle assessment (LCA) is a very powerful tool which enables decision-makers to take into account the environmental impacts arising from the entire product lifecycle. In the conventional LCA, defined environmental impact per functional unit of a product or service is calculated to evaluate the existing lifecycle. However, it is just the tip of the iceberg concerning the capability of LCA in decision support.

Frequently, a decision-maker's goal is to find the most favorable scenario by evaluating various possible alternatives which are generated using facts and anticipations. This process is called scenario development. Assessment of technologies, policies, and social systems should be carried out in conjunction with scenario development, i.e. scenario generation and evaluation. Therefore, integration of LCA with scenario generation and evaluation is a vital factor in bringing lifecycle thinking into a final decision.

1.1 Scenario development

Scenario development is an iterative activity. Generation and evaluation of scenarios are repeated until a scenario which can result in a favorable future is obtained.

For scenario generation, forecasting and backcasting are frequently used. Forecasting is based more or less on extrapolation of existing trends. It can provide investigators with information such as the consequence of choices when there are several possible alternatives before action. It is most useful in sounding an alarm. On the contrary, backcasting starts with the design of a desirable future and then investigates how that future can be attained. This approach helps investigators identify required changes and options that can be overlooked when using forecasting alone (Hojer and Mattsson 2000). Focusing on the use of scenarios in LCA, SETAC-Europe LCA Working Group 'Scenario Development in LCA' (Pesonen et al. 2000) identified two basic approaches for scenario generation, what-if scenarios and cornerstone scenarios. The what-if scenario is used to compare two or more options in a situation that is well known to the investigator. In such a study, the assumptions may be based on existing data. The study provides quantitative comparisons among the options that are well studied and do not have many differences in a small-scale system with a short time horizon. On the contrary, the cornerstone scenario is an approach used to put 'cornerstone' alternatives in new and unknown problem domains, where long-term and strategic information is required. This kind of study does not necessarily yield quantified results. Investigators choose several options which might be very different. Alternatives based on these options serve as 'cornerstones' of the field of interest, and thus, the results provide investigators with an overall view to reperceive the reality.

Scenario evaluation is used for assessment of future situations under a given scenario. There are various viewpoints considered for the assessment, such as cost, risk, safety and environment. Usually, the role of evaluation is not directly in decision making, but in posing the basis for decision making by clarifying the tradeoffs among these viewpoints. When either the extracted tradeoffs are solved by generating a different scenario, or decisions that balance the tradeoffs are made, the most favorable scenario is drawn out as the output of scenario development. Best-case and worst-case scenarios are evaluation techniques frequently used to assess the validity of the evaluation. In the best-case scenario, the best possible assumption is made in order to perceive the upper limit of the uncertainty. The worst-case scenario is the opposite; here, the lower limit of the uncertainty is observed.

In order to bring a lifecycle perspective into scenario development, LCA methodology can be considered as one of the most useful devices. The LCA framework defined in ISO14040 (ISO 1997) does not explicitly include scenario development in its covered usage. However, a number of scenario studies have been reported, adapting the LCA framework for their specific case objective (McLaren et al. 1999, Miyamoto et al. 2000, Shimada et al. 2000). In these studies, the possible future situations are simulated by constructing models, which include process chains, specific conditions and assumptions. The results obtained from such simulations clarify the differences of the material and energy flows at the boundary of a lifecycle system for a certain scenario from those for a base-case scenario. Then they are converted into some indicators using LCIA methodologies.

Since scenarios inherently deal with the past, present, and future situations, including the paths among them, time-dependent conditions and effects should be taken into account in scenario development. Dynamic LCA methodology has been proposed for this purpose (Shimada et al. 2000). The dynamic LCA is inevitable, particularly when a process exists in the lifecycle system, where products take a relatively longer time to go through than other processes. The process of consumption of a long-lifetime product is an example.

1.2 Need for accumulating knowledge

Even if the methodology of the scenario development is established and even if it is integrated with LCA, it must be noted that extended use of LCA for scenario development is a costly activity. Since there is little accumulated knowledge about the scenario development and a scenario always includes non existent processes, the model to be evaluated must be constructed from the very beginning and the data collection may be more difficult than in the conventional LCA studies. Therefore, accumulation of knowledge about the scenario development must increase reusability of models and data.

It is said that transparency of the model, data and assumption is important to validate LCA results. More efforts to assure transparency are needed in the novel applications of LCA to scenario development, because of the increased complexity and uncertainty in models and data. Reviewability is a crucial issue for the validation of an LCA study. Several possible efforts can be considered to comply with these issues. The development of standardized software tools is thought to be a practical solution, because good software tools, including user interfaces, provide users with a clear description of the framework and language, as well as a means to communicate knowledge in a common way among the users and reviewers. Although knowledge in the LCA and scenario development is presented in both data and models, knowledge is not only the data and model itself, but also the art of modeling. Thus, compilation and structuralization of useful patterns in modeling by standardized representation are the other valuable ways to enhance reusability and reviewability.

In this paper, we first propose a general framework for scenario-based LCA, an integration of LCA and the scenario development in section 2. Secondly, we introduce the lifecycle modeling language (LCML), a tool for modeling under the proposed framework, in section 3. LCML has three equivalent representations, each for different purposes required for the functionality of the language. In addition, the framework and LCML are demonstrated through an illustrative example in section 4.

2 General framework of scenario-based LCA

The SETAC Working Group on Scenario Development in LCA suggested the following definition of a scenario in LCA studies (Pesonen et al. 2000): "A scenario in LCA studies is a description of a future possible situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future." Following this definition, we propose a general framework for scenario-based LCA to enable a concretely structuralized view and to facilitate knowledge accumulation from scenario studies in LCA.

Scenario-based LCA studies reported in the literature (McLaren et al. 1999, Miyamoto et al. 2000) can be redescribed using the proposed framework, although they are not implemented to be fully compatible with it. Most of the models developed in previous studies include predefined specifications and implicit assumptions. Redescription using this framework allows us to clarify the structure of a model and thus increase the reviewability of studies.

2.1 Scenario development and scenario-based LCA

In preparation, a general framework of scenario development is drawn in **Fig. 1**. Scenario development is an activity performed to obtain the most favorable scenario from needs determined in a decision-making activity. In order to obtain the most favorable scenario, different kinds of scenarios are generated using techniques such as forecasting and backcasting. The generated scenarios are evaluated from the viewpoints of the decision-maker's needs, and the result is then returned to the scenario generation which continues until the most favorable one is obtained. In this framework, three models must be constructed and organized for scenario development as shown in **Fig. 2**. Conventional LCA inherently

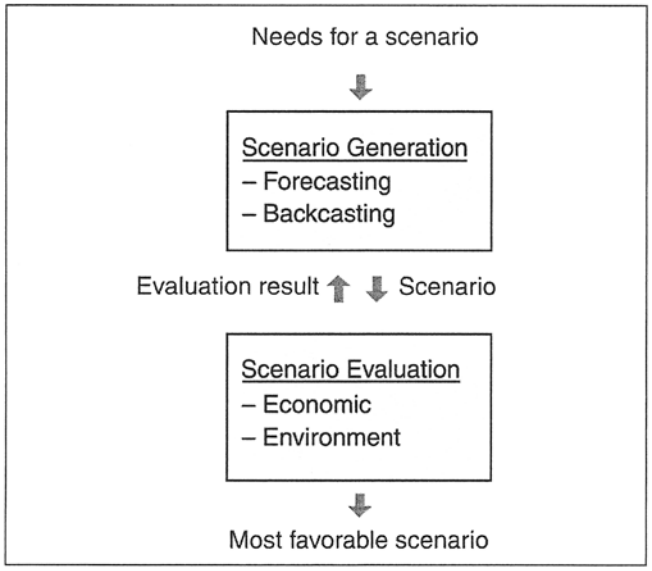
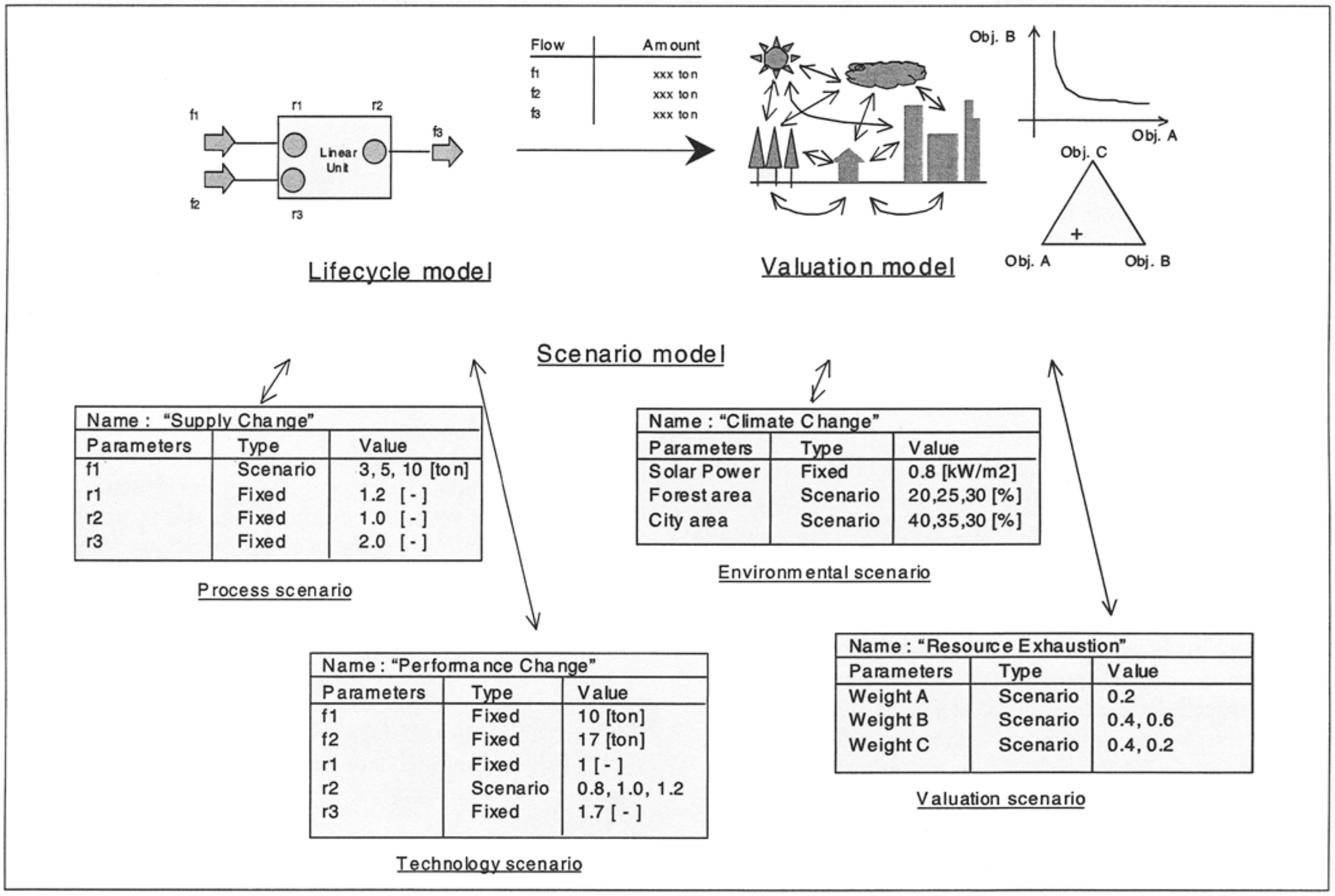


Fig. 1: General framework of scenario development



Flow	Amount
f1	xxx ton
f2	xxx ton
f3	xxx ton

Name : "Supply Change"		
Parameters	Type	Value
f1	Scenario	3, 5, 10 [ton]
r1	Fixed	1.2 [-]
r2	Fixed	1.0 [-]
r3	Fixed	2.0 [-]

Process scenario

Name : "Climate Change"		
Parameters	Type	Value
Solar Power	Fixed	0.8 [kW/m2]
Forest area	Scenario	20,25,30 [%]
City area	Scenario	40,35,30 [%]

Environmental scenario

Name : "Performance Change"		
Parameters	Type	Value
f1	Fixed	10 [ton]
f2	Fixed	17 [ton]
r1	Fixed	1 [-]
r2	Scenario	0.8, 1.0, 1.2
r3	Fixed	1.7 [-]

Technology scenario

Name : "Resource Exhaustion"		
Parameters	Type	Value
Weight A	Scenario	0.2
Weight B	Scenario	0.4, 0.6
Weight C	Scenario	0.4, 0.2

Valuation scenario

Fig. 2: Relationships among lifecycle model, valuation model and scenario models

involves two models, a lifecycle model used for lifecycle inventory analysis (LCI) and a valuation model used for lifecycle impact assessment (LCIA). A lifecycle model represents a process chain connecting process sub-models, which represents the relationship between input and output flows. Using the lifecycle model, the total amounts of input and output flows of the entire lifecycle (input and output flow indices) are yielded. A valuation model converts these flows into several indicators. If the investigator is interested in the global warming problem, global warming potential (GWP) may be calculated using the amounts of output flows of green-house effect gases. The valuation model may contain a weighting procedure to unify multiple indicators.

In addition to these models drawn on the upper part of Fig. 2, we introduce a scenario model for scenario-based LCA in the lower part of Fig. 2, where four examples of scenario models are shown; process, technology, environmental and valuation scenarios. They represent models to evaluate supply change, process performance change, climate change and multiple resource exhaustion, respectively. We consider that a scenario is described by scenario parameters and assumptions. As a result, a scenario model is defined by a categorized set of every possible parameter existing in the lifecycle and valuation models. We identified that there are two categories in scenarios which correspond to the two models in the conventional LCA. Scenarios that have the same amount of flows or process parameters as the scenario parameter can be categorized in the same group, since they are relevant only with the lifecycle model. The process and technology scenarios in Fig. 2 are classified into this category. On the contrary, scenarios introducing change in an environmental system or in the public sense of values can be grouped into another category, since they are only relevant

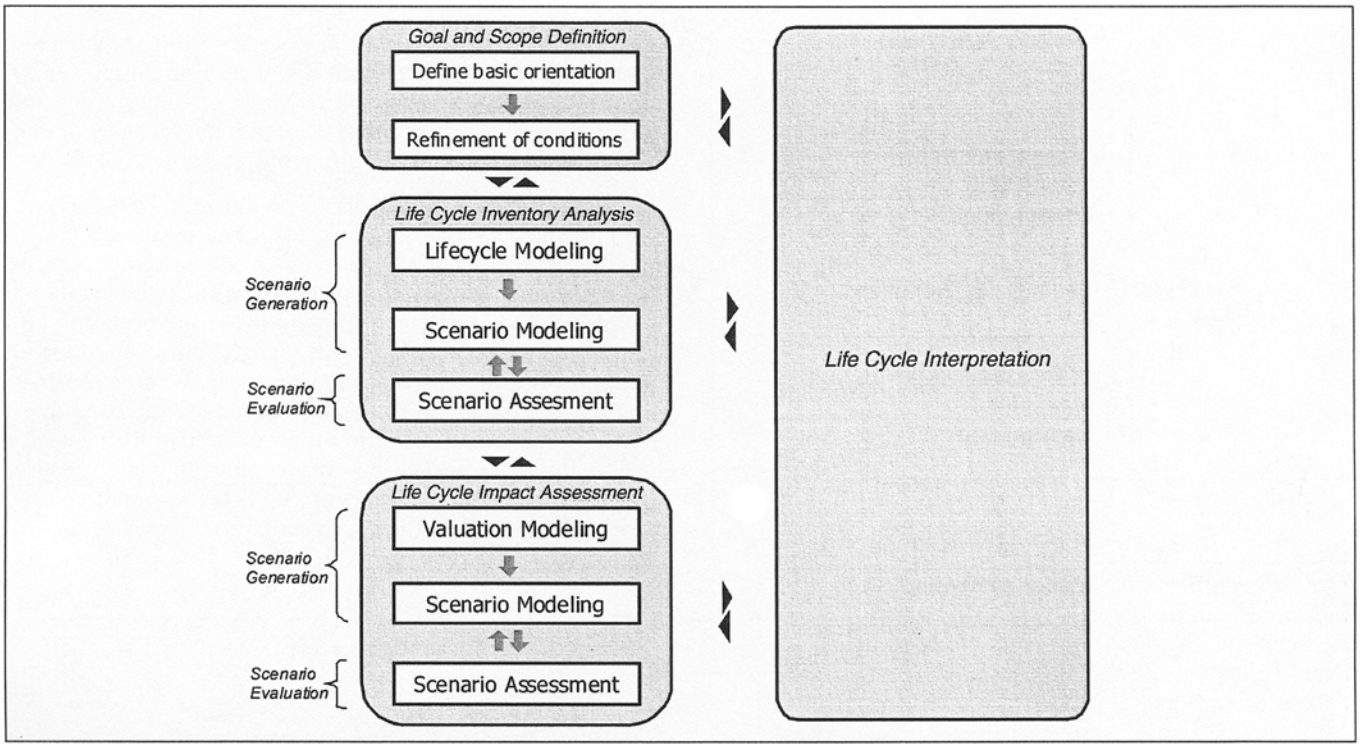


Fig. 3: General framework of scenario-based LCA

with the valuation model. The environmental and valuation scenarios in Fig. 2 are classified into this category. A specific scenario can be described as a logical summation of these two categories. The scenario model is developed to enhance the conventional models so they are capable of scenario development. Description of a scenario-based LCA study appears as a coupling of these three models.

The general framework of scenario-based LCA derived from Figs. 1 and 2 is presented in **Fig. 3**. The three procedures in the lifecycle inventory analysis stage produce inventory data from the target lifecycle system boundary. The three procedures in the lifecycle impact assessment stage produce indicators which are used for decision making. Each group is divided into scenario generation and evaluation from the scenario development perspective. This framework of scenario-based LCA involves two iterative procedures for scenario development. In the first procedure, the lifecycle model is developed based on the goal and scope definition of the study, which will be discussed in section 2.6. Then, the scenarios in consideration are classified into two categories and scenario models relevant to the lifecycle model are constructed by categorizing parameters in the lifecycle model, collecting necessary data, and making assumptions. Using the models constructed so far, input and output flow indices of materials and energy are obtained. They are transferred to the second iterative procedure. An adequate impact assessment methodology is chosen and modeled as a valuation model, and then the scenario model relevant to the valuation model is constructed. Finally, the indicator is calculated. If the result of the scenario assessment satisfies the investigator's requirements, the most favorable scenario is developed.

2.2 Lifecycle modeling

The lifecycle model in the proposed framework is a process chain model including various constraints and interactions. The structure of relationships between parameters and the degree of freedom in the scenario is governed by this model. Dynamic aspects of parameters are also described in this model. However, the lifecycle model only prescribes the structure of relationships between parameters in this framework. None of the values of parameters are specified in a lifecycle model. Its role is limited to expressing the structure of the relationship between all parameters in the target system. Parameter values are treated in the scenario model.

Although the number of individual lifecycle systems that can possibly be a target of analysis is large, each one can be broken down into a series of similar relationships that are commonly used in different models. These relationships are based on the same mathematical principles and are dispatched with sub-models in the process chain. The types of each of the sub-models are defined in the implementation based on this framework.

Fig. 4 illustrates the most simple lifecycle model with two input and one output flows including six parameters. Fig. 4 (a) and (b) show a static model and a dynamic model with delay attributes, respectively. They are drawn using LCML, an implementation of the proposed framework described in section 3. The box here represents a 'linear unit' in LCML, which represents the constant conversion ratio. The conversion ratio is the ratio between flow rates and is signified with a circle inside the box. The degree of freedom of this lifecycle model is four in any case, which means that four values of the six parameters must be set to determine all of

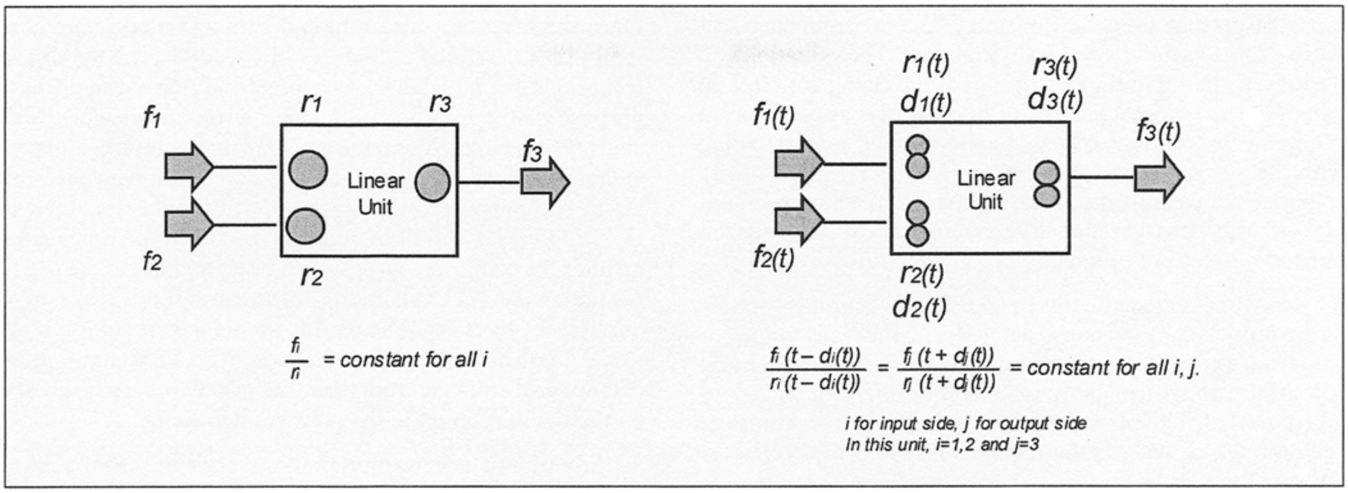


Fig. 4: Lifecycle model with two input and one output flows

the parameters in this model. Note that not only the flow rate, but also the specification of the relationships such as the conversion ratio in the linear unit can be a parameter in a lifecycle model. Figure 4 (b) depicts the same model with dynamic extension. The box here is also a linear unit, but dynamic attributes are defined. In our framework, time is not a parameter itself, but an attribute for other parameters. In addition to the time attribute, each flow requires a certain amount of time for processing. Therefore, the delay factors ($d_1(t)$, $d_2(t)$, and $d_3(t)$) are defined as a parameter in the unit, in addition to the conversion ratios at every time step. Values of input and output flows are associated with one another in the dynamic linear model.

2.3 Valuation modeling

Changes in flow rates corresponding with changes in scenario parameters are interpreted into a certain form using valuation models. This model is constructed by investigators to meet their interests, cases, and sense of values. The role of the valuation model involves LCIA procedures such as classification, characterization, damage estimation, and weighting.

The major issue in valuation modeling within scenario-based LCA is that there are not many LCIA methodologies fully capable of dynamic evaluation. If we use cumulative emission factors, which are environmental impacts associated with a functional unit calculated by the retrospective LCA method, the dynamic aspect of the analysis would not be reflected properly. It must be noted that the conventional inventory data for LCI does not provide sufficient information to perform dynamic analysis. Extension is needed both in data model and LCIA methodologies, otherwise we have to use the complicated and rare results from flow calculation for assessment, or integration of environmental load over a period described in a scenario using the static methods.

Valuation models may involve time dependent parameters, which are not fixed in the focal time period. For example, cumulative emission factors for utilities will be frequently selected as a scenario parameter to represent the evolution of the technology. Weighting factors for different impact categories is another possible candidate for scenario parameters to reflect the change in significance of each impact category in society. Therefore, scenario models are also constructed for parameters in the valuation model.

2.4 Scenario modeling

According to the definition of a scenario by the SETAC Working Group (Pesonen et al. 2000), 1) possible future situation, 2) assumptions about the future, and 3) presentation of development from the present to the future should be expressed within the framework. In the proposed framework, they are expressed as scenario models.

A scenario model is a categorized set of parameters that are involved in the corresponding lifecycle model and valuation model. There are three types of parameters; fixed parameters, scenario parameters and other parameters. Note that time is not treated as a parameter in our framework. Evolution of time is an inherent scenario parameter in every scenario which cannot be controlled in an analysis. Instead, time is an attribute for every parameter. A parameter can be categorized into different types according to its different time attributes. However, the categorization itself cannot be changed dynamically in a scenario model.

A parameter whose value is constant through any situation in the scenario is categorized as a fixed parameter and its value is specified in the scenario model. A parameter that can be explicitly changed by a scenario investigator is categorized as a scenario parameter. The changes in the amounts of scenario parameters express the transition of states or situations through the scenario. The rest of the parameters are categorized as other parameters, which can be determined according to the degree of freedom in the lifecycle model and valuation model. Degree of freedom is determined according to the number of parameters and the structure of the models.

We identified four types of scenarios, the technology scenario, process scenario, environmental scenario, and valuation scenario, as shown in Fig. 2. The technology scenario describes the change of performance within a process due to the evolution of technology. The process scenario has flow rates or mechanisms that affect the flow rates. The environmental scenario expresses the change in environment. The valuation scenario is in charge of the description of the change in sense of values of the stakeholder. The technology scenario and process scenario are modeled as scenario models corresponding with the lifecycle model, and the environmental scenario and valuation scenario are modeled as scenario models corresponding with the valuation model. A scenario model can be developed as a hybrid of different types of scenarios.

As described schematically in Fig. 2, any number of scenario models can be constructed for a lifecycle model or valuation model. This means that the lifecycle model and valuation model can be reused among different scenarios when needed. This structure assures the direct reusability of each model, as well as the reviewability and indirect reusability of the entire study.

2.5 Scenario assessment

Using the scenario model, all values of the parameters in the lifecycle model are determined. Values of scenario parameters and fixed parameters are provided by a scenario. All other parameters are calculated according to the relationships prescribed by respective lifecycle and valuation models. A combination of the lifecycle model and scenario model produces indices of material and energy flows, which are used in the valuation model corresponding to the first part of scenario-based LCA shown in Fig. 3. On the other hand, a combination of the valuation model and scenario model results in evaluation. This combination corresponds to the latter part of Fig. 3.

Actually, a part of scenario assessment is already performed when scenario models are constructed, because the determination of parameters is performed both in scenario assessment and in scenario modeling, where we categorize parameters into fixed, scenario, and other parameters and give actual values to the fixed parameters.

Scenario-based LCA studies reported in the literature (McLaren et al. 1999, Miyamoto et al. 2000) can be redescribed using this framework, although they are not implemented to be fully compatible with it. Most of the models developed in previous studies include predefined specifications and implicit assumptions. Redescription using this framework allows us to clarify the structure of a model and thus increase the reviewability of studies.

2.6 The goal and scope definition and interpretation stages

In the scenario-based LCA framework, goal and scope definition and interpretation stages play quite a fundamental role. At the goal and scope definition stage, a basic orientation of scenario development should be defined. In this stage, results from other preliminary analyses may provide insights to the scenario development. Let us consider a case whose basic orientation is to substitute a product with a different product. Results from conventional LCA may provide a basic supporting knowledge to decide the basic orientation, whether or not to substitute the product, before going into scenario-based LCA procedures.

Once the lifecycle, valuation, and scenario models are constructed as described in the previous sections, the developed scenario is examined in the interpretation stage. The primary purpose of the interpretation stage in this framework is to analyze results, reach conclusions, explain limitations and provide recommendations in a form of a scenario, which is similar to the purpose of life cycle interpretation described in ISO14043 (ISO 2000). In addition, modification and refinement of the scenario, which would be equivalent to the modification in lifecycle, valuation, and scenario models, are other important objectives. The path from the interpretation stage to the goal and scope definition stage makes a scenario more detailed and strategic from the more primitive scenario based on the orientation set in the previous iteration.

Sensitivity and uncertainty analyses offer important information to the latter objectives, as well as to the former objective in the ways described in ISO14043. Sensitivity analysis provides information that shows which parameter may well be added to or excluded from the current set of scenario parameters. Justification of the boundary of the lifecycle model also requires sensitivity analysis. In the scenario, not all of the process is well known. Thus, there is a vital need for setting assumptions in the inventory data, and such assumptions should be checked if their entailing uncertainty matters in the result.

3 Lifecycle modeling language (LCML)

The framework provides the conceptual foundations for the execution of scenario development and for accumulation of knowledge generated in scenario-based LCA studies. For investigators, however, the framework is not sufficient to carry out actual scenario development. In addition, an actual substance of the framework should be supplied as well. We developed a tool, termed lifecycle modeling language (LCML), for modeling of a lifecycle system and its relevant scenarios. This tool is a modeling environment in the form of a computer software system which has three requirements; 1) a complete implementation of the framework presented in section 2, 2) a graphical user interface for standardized communication between investigator and computer, 3) a flexible format of data and model to accumulate knowledge and to exchange knowledge among investigators and different software systems. These requirements are realized by providing different variations of LCML representation, which are graph representation, Java™ representation, and XML (extensible markup language) representation. Note that they represent the same models and can be converted to each other by using the tools we provide, as shown in **Fig. 5**.

Graph representation is in the form of documents with graph, table and essential descriptions. The structure of a lifecycle model is described visually by using several basic shapes such as boxes and arrows as shown in Fig. 4. Various types of units, which are sub-models in a process chain, are made to correspond to these shapes, and the details of each model element are described in text documents. The scenario model is described in a table, together with the corresponding lifecycle model.

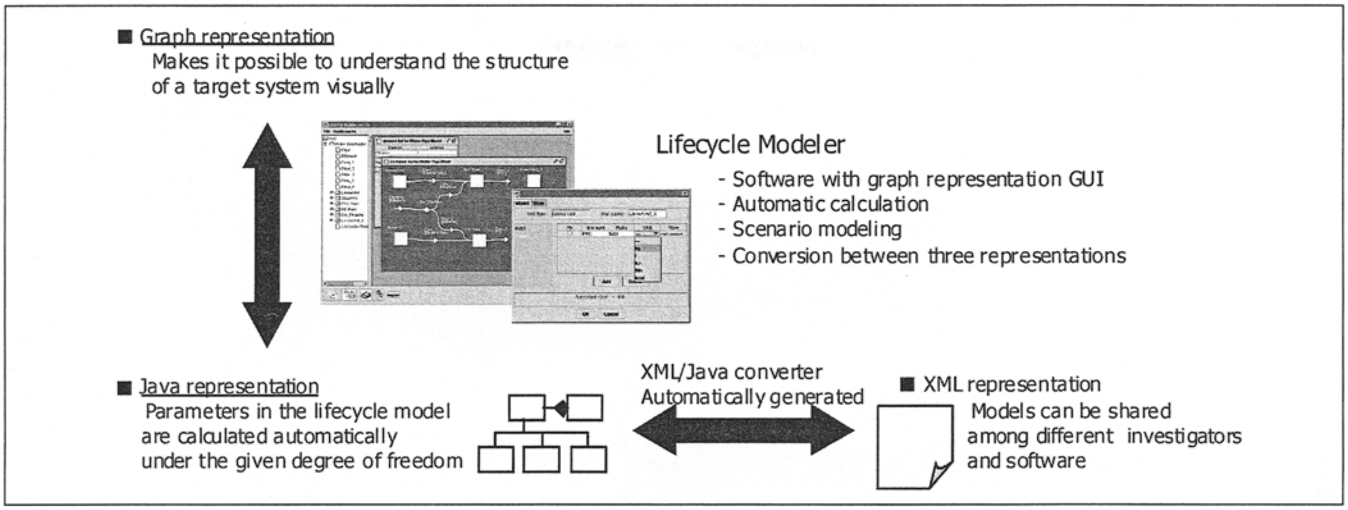


Fig. 5: Three represenations of LCML and related tools

Java™ is an object-oriented programming language widely used for recent software development. Using Java representation of LCML, the models are implemented as objects, building blocks comprising software systems. Therefore, all the calculations that are needed in the scenario assessment can be carried out. This characteristic, the equivalency of modeling and programming, inherently comes from object-oriented architecture. We developed the Lifecycle Modeler, software equipped with a graphical user interface based on the LCML graph representation. Using this software, investigators can carry out lifecycle modeling using graph representation, and the Java model is concurrently constructed using Java representation. Thus, graph representation and Java representation are convertible.

XML is a meta-language, a language used to define a new language. We decided to develop the XML representation of LCML, to transfer models from software to data, which can be distributed among different software systems. XML has many support utilities, such as tools for automatic generation of software modules that can handle a specific language defined using XML. This functionality assures the convertibility between Java representation and XML representation.

We can find two successful analogous cases from other fields, that accumulate knowledge by pattern recognition using language designed for the problem domain. The first example is flow sheeting in chemical process design (Duncan and Reimer 1998, Himmelblau and Bischoff 1968). Unit operations in chemical engineering served as a useful vocabulary in the language, the flow sheets used for accumulating knowledge generated in the chemical process design. The second example is the unified modeling language (UML) in software engineering (OMG 1999). UML provides system architects using object-oriented software design methodologies with one consistent language for specifying, visualizing, constructing, and documenting the artifacts of software systems. Various useful design patterns are recognized and the pattern catalogue is referred to very frequently during the object-oriented software design activities (Gamma et al. 1995). The underlying common principle in these cases is to define a domain-specific vocabulary, to facilitate the description, to make a pattern catalogue through pattern abstraction from the actual cases, and to associate actual examples with each pattern.

LCML has a set of models of process units, which are useful components to describe a lifecycle model. These unit models, used as sub-models for lifecycle models, were identified from a number of case studies. By using these unit models, description of a lifecycle model is simplified. Likewise, the further development of LCML and case studies should be carried out complementarily.

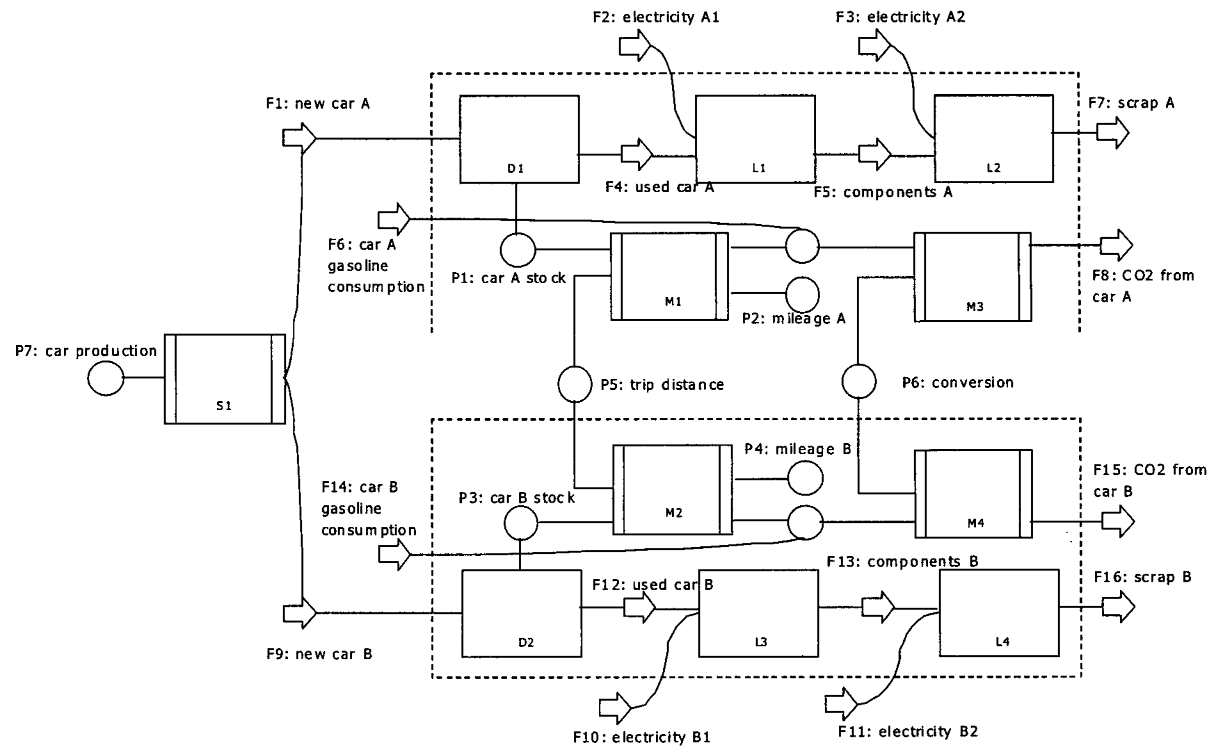
4 Illustrative Example

In this section, the usage of LCML is illustrated using an example of a car selection and product transition scenario.

4.1 Car selection and development of product transition scenario

There are several possible alternatives in technologies that are used for improving the environmental performance of cars. When these technologies are to be introduced, they must be investigated in advance, from the lifecycle perspective. As an example, we generate and evaluate a scenario named 'Car product transition scenario'.

We assume that the car manufacturer developed a new car, car B, which was equipped with a more efficient engine system than that of car A. Car A has already been produced and been on the market for the past twenty years. The retrofit of the engine system achieved a 50% increase in the mileage efficiency. On the other hand, the electric power consumption in the scrapping process of car B increases it to 200% of that of car A. CO_2 emission is chosen as the sole environmental indicator of the evaluation. From a result of retrospective static LCA proved that the lifecycle CO_2 emission of car B is less than that of car A. Although the investment cost to change the production system from car A to car B is considerably high at this moment, it is expected to decrease in the near future. The present interest of the decision-maker lies in the exact trade-off between CO_2 emission and the expected cost. The scenario-based LCA should be



Unit	Type	Description
D1	Distribution	Car A Use
D2	Distribution	Car B Use
L1	Linear	Car A Dismantling
L2	Linear	Car A Scrapping
L3	Linear	Car B Dismantling
L4	Linear	Car B Scrapping
S1	Summation	car production = new car A + new car B
M1	Multiplication	car A stock × trip distance = mileage A × car A gasoline consumption
M2	Multiplication	car B stock × trip distance = mileage B × car B gasoline consumption
M3	Multiplication	car A gasoline consumption × conversion = CO2 from car A
M4	Multiplication	car B gasoline consumption × conversion = CO2 from car B

Fig. 6: Lifecycle model of car product transition scenario

used for scenario development and time-dependent assessment of such a situation, starting from the definition of basic orientation (replace car A with car B) as described above. Taking into account the lifetime of both cars (both 10 years), the focal period starts at thirty years ago and ends at forty years in the future. The demand of car use and the cumulative emission caused by car production and the scrap usage are assumed to be constant throughout the focal period. Lifetimes of both cars are assumed as a normal distribution with an average of ten years and variation of two years, which do not influence each other. There is a constraint that the number of cars which can be produced is constant.

The lifecycle model of the car product transition scenario is described using LCML as shown in **Fig. 6**. The cars are used by a consumer (Units D1, D2), dismantled into the components (Units L1, L3), and finally scrapped (Units L2, L4). Recycling is not considered in this example. Electric power is used for dismantling (Flows F2, F10) and scrapping (Flows F3, F11). Gasoline consumption (Flows F6, F14) and direct CO_2 emission from car use (Flows F7, F15) are calculated from the mileage efficiency of each car (Parameters P2, P4), trip distance per year (Parameter P5), and the stock in the market (Parameters P1, P3). Here, we concentrate on the production capacity constraint on parameter P7. Other interactions, which may be caused between two car lifecycles, are not included in this example. The model does not include upper streams including the production stage, since we assume here that both cars are produced with an equivalent usage of materials and energy. The processes after scrapping are also ignored, as the treatment of car scrap is the same for both cars.

In the LCML graph representation, a box arrow represents a flow, and a circle depicts a parameter. In addition, four kinds of unit models are used in the lifecycle model of this example. They are categorized into two groups; parameter and flow unit. Every model element is given a unique name.

A parameter unit, expressed as a box with a double line on the side, is used to express various relationships among two or more parameters and flows. In this example, a summation unit, S1, is used to equilibrate the sum of parameters connected on one side and that on another side. Multiplication units, M1 to M4 can be used likewise, in case we need to use the multiplication operation instead of the summation operation.

A flow unit, expressed as a box, represents an activity, including a process, operation or reaction, whichever changes the attributes of flows such as its element and amount, according to the allocated parameters that are specifically defined for each type of unit. In this example, linear units, L1 to L4 are used to represent car dismantling and scrapping processes, which are assumed to have input and output flows that obey the linear relationships. A distribution unit is another variation of flow units used in this example. The input to this unit is stored for a certain period following a given lifetime distribution. Car consumption processes, D1 and D2, are expressed using the distribution unit.

In this investigation, we look at the effect of changing the product from car A to car B, where the physical resources for production are limited. This limitation is set by selecting the overall car production, P7, as a scenario parameter together with the production rate of car A, F1. The time step starts from –30, to prepare the situation that car A is on the market at year 0. The car production is switched from car A to car B in the 0-th year. Parameters involved in a unit, such as the conversion ratio in the linear units and lifetime distribution of both cars in the distribution unit are set as fixed parameters in this scenario model. In addition, the mileage of both cars, P2 and P4, service provided by a car per year, and conversion from gasoline to CO_2, P6, are also provided as fixed parameters. The stock of each car at the start of the production is required for the calculation. Other parameters involved in the lifecycle model are calculated from the fixed and scenario parameters, where the degree of freedom is satisfied. The scenario model relevant to the lifecycle model in this scenario is summarized in **Table 1**. In scenario models, the basis of given values should be described. As described, all of the values are hypothetically set in this example. Note that all model elements: flows, parameters, flow units, and parameter units are given a unique name. The different rows in Table 1 that have the same name entry describe the same parameter, each of which has a different time attribute. From the lifecycle model and scenario model constructed so far, flow indices can be calculated as shown in **Table 2**. LCML Java representation is used for all calculations.

The total CO_2 emission is the sole focus in the evaluation performed in this example. The Input/Output (I/O) flow indices are converted into CO_2 emission using the cumulative CO_2 emission factor in the valuation model. It should be noted that it is assumed that all CO_2 emission, which arises beyond the lifecycle model boundary, takes place within the same year

Table 1: Scenario model (relevant to lifecycle model) for car product transition scenario

Unit	Name	Value	Unit	Time	Type	Basis
–	new car A	0	[cars/year]	before –21	Scenario	Imaginary
–	new car A	10,000	[cars/year]	–20 to 0	Scenario	Imaginary
–	new car A	0	[cars/year]	1 to 40	Scenario	Imaginary
–	car production	0	[cars/year]	before –21	Scenario	Imaginary
–	car production	10,000	[cars/year]	–20 to 40	Scenario	Imaginary
–	car A stock	0	[cars]	before –21	Fixed	Imaginary
–	car B stock	0	[cars]	before 0	Fixed	Imaginary
–	mileage A	10	[km/kg]	entire period	Fixed	Imaginary
–	mileage B	15	[km/kg]	entire period	Fixed	Imaginary
–	trip distrance	1,000	[km]	entire period	Fixed	Imaginary
–	conversion	2.31	[kg-CO_2/kg-gasoline]	entire period	Fixed	Imaginary
D1	new car A	N(10,2)[a]	N([year], [year])[a]	entire period	Fixed	Imaginary
D1	used car A	N(10,2)[a]	N([year], [year])[a]	entire period	Fixed	Imaginary
L1	used car A	1	[cars]	entire period	Fixed	Imaginary
D2	new car B	N(10,2)[a]	N([year], [year])[a]	entire period	Fixed	Imaginary
D2	used car B	N(10,2)[a]	N([year], [year])[a]	entire period	Fixed	Imaginary
L3	used car B	1	[cars]	entire period	Fixed	Imaginary
L1	electricity A1	1	[kWh]	entire period	Fixed	Imaginary
L2	electricity A2	0.5	[kWh]	entire period	Fixed	Imaginary
L3	electricity B1	1	[kWh]	entire period	Fixed	Imaginary
L4	electricity B2	1	[kWh]	entire period	Fixed	Imaginary
L1	component A	1,000	[kg]	entire period	Fixed	Imaginary
L2	component A	1	[kg]	entire period	Fixed	Imaginary
L3	component B	1,000	[kg]	entire period	Fixed	Imaginary
L4	component B	1	[kg]	entire period	Fixed	Imaginary
L2	scrap A	1	[kg]	entire period	Fixed	Imaginary
L4	scrap B	1	[kg]	entire period	Fixed	Imaginary

[a] N(m,v) stands for normal distribution with mean m and variation v

Table 2: Flow rates in the car product transition scenario

Flow	I/O	Name	Unit	Value (time)
F1	Input	new car A	[cars]	0 (–30 to –21), 10,000 (–20 to 0), 0 (1 to 40)
F2	Input	electricity A1	[kWh]	0 (–30 to –15), 51.73 (–14), 349.40 (–13), ...
F3	Input	electricity A2	[kWh]	0 (–30 to –15), 25,863.77 (–14), 17469951 (–13), ...
F6	Input	car A gasoline consumption	[kg]	0 (–30 to –21), 10,000 (–20 to 0), 20,000 (–21), ...
F7	Output	scrap A	[kg]	
F8	Output	CO_2 from car A	[kg-CO_2]	0 (–30 to –21), 100,000 (–20), 2,000,000 (–19), ...
F9	Input	new car B	[cars]	0 (–30 to 0), 10,000 (1 to 40)
F10	Input	electricity B1	[kWh]	0 (–30 to 6), 51.73 (7), 349.40 (8), ...
F11	Input	electricity B2	[kWh]	0 (–39 to 6), 51,727.55 (7), 349,399.02 (8), ...
F14	Input	car B gasoiline consumption	[kg]	0 (–30 to 0), 6,666,666.67 (1), 1,333,333.33 (2), ...
F15	Output	scrap B	[kg]	
F16	Output	CO_2 from car B	[kg-CO_2]	0 (–30 to 0), 154.000 (1), 3,080,000 (2), ...

Table 3: Scenario model (relevant to valuation model) for car product transition scenario

Name	Value	Unit	Time	Type	Basis
Gasoline Production	0.6517	[kg-CO_2/kg-Gasoline)	entire period	Fixed	Imaginary
Electricity	0.357	[kg-CO_2/kWh]	entire period	Fixed	Imaginary

of production. Otherwise, the time profile of the CO_2 emission cannot be traced, but even in such cases, the integral emission can be observed properly. The scenario model corresponding with the valuation model is shown in Table 3.

Time profiles of input and output flows passing through the model boundary are translated into lifecycle CO_2 emission as shown in Fig. 7. The CO_2 emission at the steady state that is observed from time –10 to 0 (car A) and from time 13 to the end (car B) is simply assessed using the conventional type of LCA. Scenario-based LCA provides more detailed results, such as the CO_2 emission at the transitional state.

The result shown in Fig. 7 indicates that the effect of a replacement of products is evident with time lag. During replacement, the CO_2 emission is evident as a result of dismantling and scrapping, after the emission decreases due to an improvement in the mileage efficiency. This interpretation may lead to the modification of the scenario, which takes the evolution of the dismantling and scrapping technology into account. Clarification of the relationship between technology development and resulting emission would be added into the scope of the study, and a new parameter would be added to the previous set of scenario parameters in the scenario model.

4.2 Demonstration of reviewability, reusability, and accumulation of knowledge

In this section, increased reviewability of the study, reusability of models, and accumulation of knowledge in lifecycle modeling are sketched out.

Reviewability is important, because all data of a study should be available for a credibility check for validation of the study. As is evident in this example, defining parameters and assigning values to the parameters are separate tasks. The former is performed in lifecycle model and the latter in the scenario model. This feature prevents us from overlooking the existence of implicit data in the model, and clarifies the structure of the scenario. In the example, we had to set the scenario period from the year –30, which may appear to be irrelevant but in fact is not, since the number of cars stocked in the market and its time profile are required for the calculation for the time period we

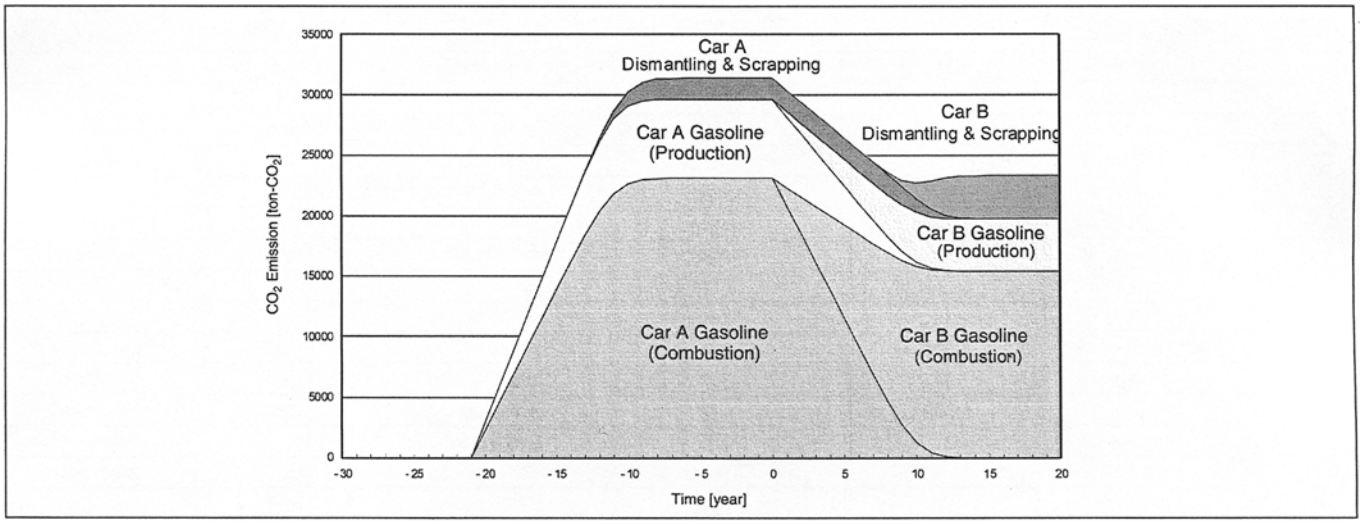


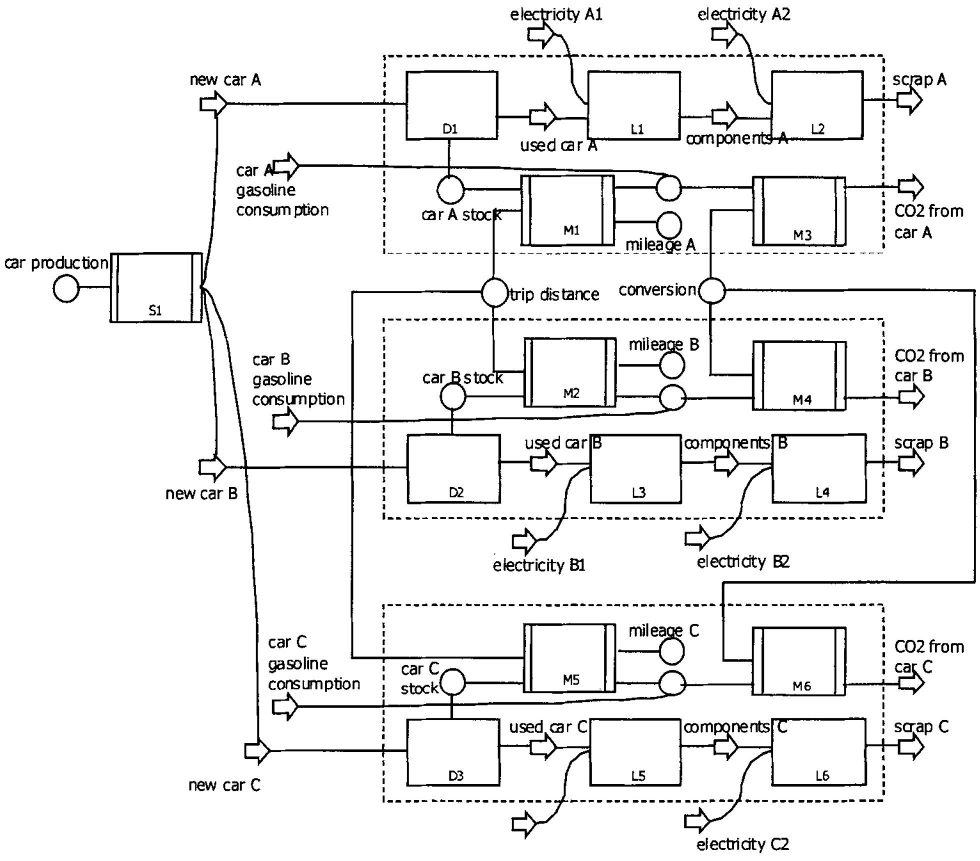
Fig. 7: Timeprofile of lifecycle CO_2 emission

are looking at. This kind of implicit information might be overlooked in many cases. As another important aspect of reviewability, it should be noted that sharing information using the same language, such as LCML, could greatly facilitate communication between different investigators.

Reusability is crucial for reducing the cost of conducting a new study. Among the three types of models, the lifecycle model has great potential to be reused in other studies, since the structure of parameter relationships can be used in different contexts. In our framework, scenario and valuation models can be added by other investigators with modified data values and valuation methods, instead of starting the procedure from the very beginning. This approach reuses the lifecycle model as it is. In this example, it is easy to modify the study to consider the change in cumulative CO_2 emission factor, by adding a different scenario model. There are also possibilities to use the lifecycle models as part of the lifecycle model for a new study. It is almost a straightforward procedure to extend the lifecycle model in the example to consider the third type of car, as shown in **Fig. 8**, which gives the result shown in **Fig. 9**.

By achieving high reviewability, reusability of a study is also increased. This is because there are indirect ways of reusing a study, in addition to the direct reuse of the models. The studies can be adapted to other cases with minimum modification, if highly reviewable. The structured framework increases the reviewability of a study, and thus, the indirect reusability is increased at the same time.

In the example, the distribution unit alone is not sufficient to express the car consumption process, since it cannot provide the values of inputs and outputs, which are calculated as functions of the stock in the unit, such as CO_2 emission



Unit	Type	Description
D1	Distribution	Car A Use
D2	Distribution	Car B Use
D3	Distribution	Car C Use
L1	Linear	Car A Dismantling
L2	Linear	Car A Scrapping
L3	Linear	Car B Dismantling
L4	Linear	Car B Scrapping
L5	Linear	Car C Dismantling
L6	Linear	Car C Scrapping
S1	Summation	car production = new car A + new car B
M1	Multiplication	car A stock × trip distance = mileage A × car A gasoline consumption
M2	Multiplication	car B stock × trip distance = mileage B × car B gasoline consumption
M3	Multiplication	car A gasoline consumption × conversion = CO2 from car A
M4	Multiplication	car B gasoline consumption × conversion = CO2 from car B
M5	Multiplication	car C stock × trip distance = mileage C × car C gasoline consumption
M6	Multiplication	car C gasoline consumption × conversion = CO2 from car C

Fig. 8: Extended lifecycle model for car product transition scenario

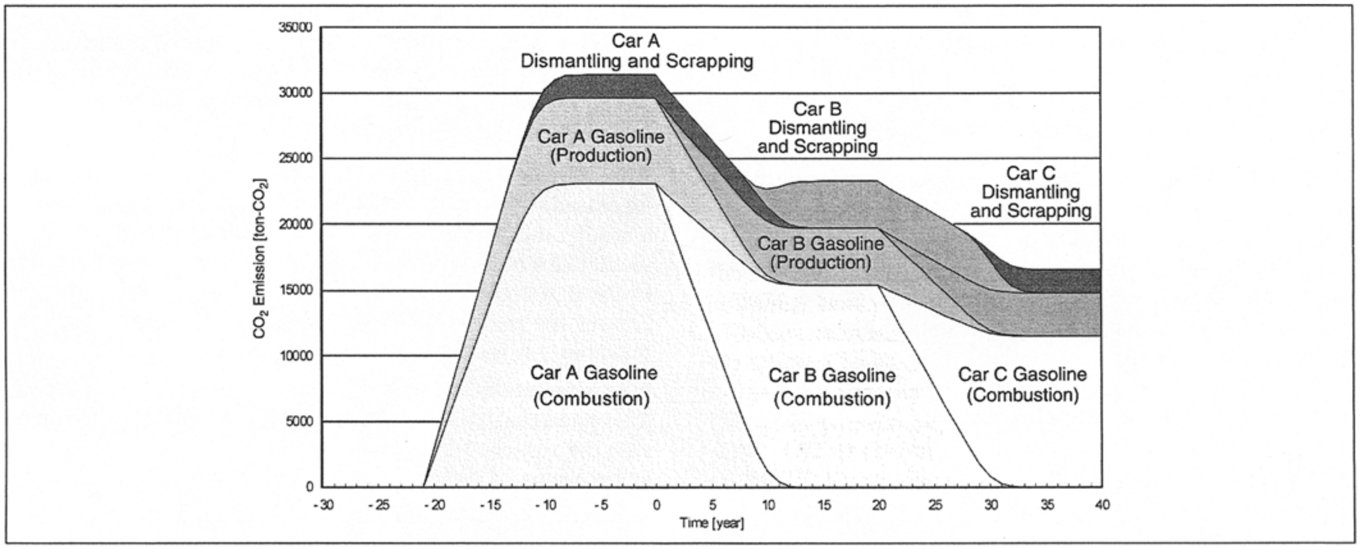


Fig. 9: Time profile of lifecycle CO_2 emission calculated from the extended model

and gasoline consumption. In such cases, two practical solutions in lifecycle modeling could be considered as follows.

The first option is to use the combination of predefined units. In the example, CO_2 emission and gasoline consumption were calculated using parameters and parameter units. This kind of possible walk around, in other words 'art of modeling', can also be effective in other situations if they are collected in a reusable way. This collection of patterns is accumulated by adding to a pattern catalog, which becomes an aid for case studies.

Defining a new unit is another option to accumulate the art of modeling. As shown in **Fig. 10**, the newly constructed model looks simple by defining a new unit. In this example, 'consumption unit' C_1 is defined by integrating D_1, M_1, M_3, and relevant parameters. As the result of integration, external parameters such as 'car A stock', 'mileage A', 'conversion', and 'trip distance' are encapsulated as more general internal parameters in the consumption unit. **Fig. 11** describes the new 'consumption unit' model. Consumption unit is defined as a unit which has two different kinds of input and output. One is the input and output drawn as single line box arrows, that are calculated in proportion to each other related to the ratio parameter $(r_{in}(t), r_{out}(t))$ and delay parameter $(d_{in}(t), d_{out}(t))$. The other is the input and output drawn as double-line box arrows that are in proportion to the stock parameter $(stock(t))$ related to the stock ratio parameter $(sr_1(t), sr_2(t))$.

5 Discussion

5.1 Integrated use of exogenous models

The proposed framework described in Fig. 3 involves one loop, which makes the scenario more detailed, and two sub-loops, each of which includes the iterative procedures in scenario development. The two sub-loops can be coupled, where the result

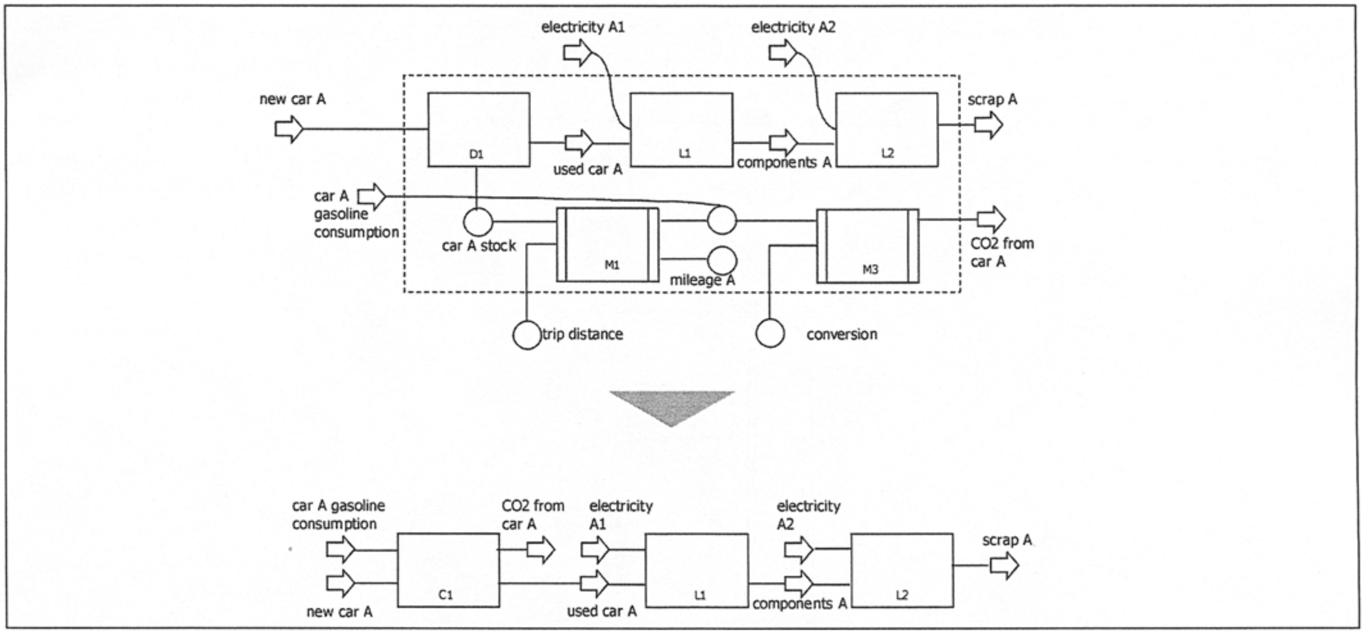


Fig. 10: Simplification of complex pattern by defining a new type of unit model

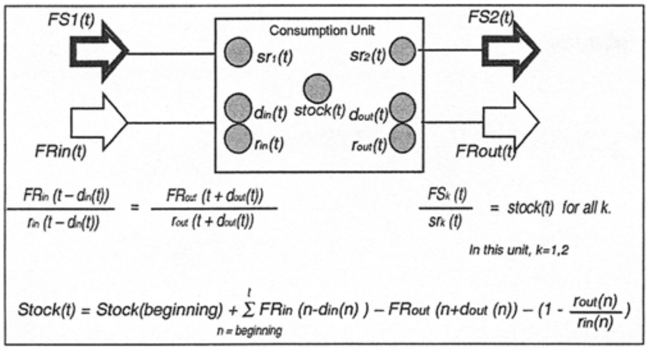


Fig. 11: Consumption unit

of the scenario-based LCA has the possibility of influencing the product lifecycle. By using the result from the valuation model as a feedback to the scenario model, the effect of communication of the result, such as the consumers' reaction to the eco-labeling, can be simulated. In order to realize such an assessment, we need exogenous models, a consumer reaction model in this case, to combine scenario models for the lifecycle and valuation models. Parameters in the lifecycle and valuation models will be associated with each other through the exogenous model, outside of the scenario-based LCA framework. Many other models can be used in a similar integrated manner, such as those simulating the effect of taxation and subsidies, prediction of future demand, and evolution of future technologies.

5.2 Two methods for accumulation of knowledge

As presented in section 4.2, there are two alternative ways to facilitate the modeling of a complex structure. One is to define a new type of unit model and another is to catalog patterns. These two means are mapped in the area prescribed by simplicity and flexibility of the identified pattern, as shown in **Fig. 12**.

Adding a new type of unit model is useful, when the pattern has a complex structure but flexibility is not needed. If a certain complex structure is frequently used for different situations with the same functionality, it is useful to define it as a new type of unit model for the structure, such as the consumption unit in the example.

On the contrary, adding patterns to a catalog is more valuable, when the pattern has a simple structure, and is adopted in diverse situations. In the example of a consumption unit, separate descriptions of 'mileage' and 'trip distance' became more complex. If one needs to select mileage as a scenario parameter, the model using the consumption unit might be constructed as shown in **Fig. 13**, which may not differ much from the original model without the consumption unit shown in the upper part of Fig. 10 from the viewpoint of complexity.

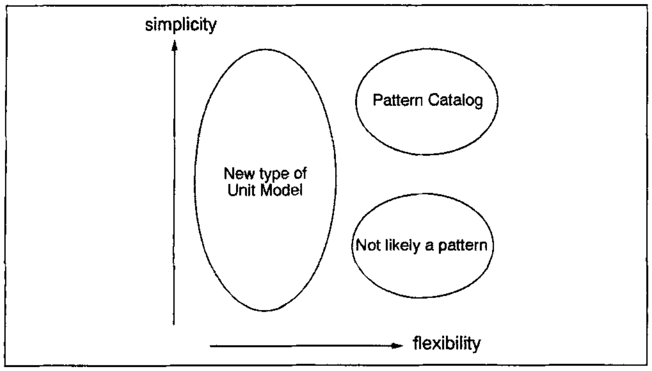


Fig. 12: Applicable means of knowledge accumulation in scenario-based LCA

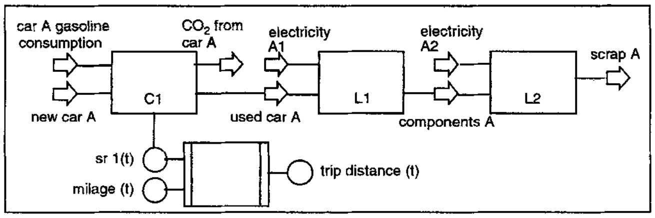


Fig. 13: Simplification of complex pattern by defining a new type of unit model

6 Conclusion

In this paper, we first discussed the scenario development as a means for decision making and proposed a general framework to perform scenario-based LCA. The framework provides scenario-based LCA studies with a more structuralized view, and foundations for accumulation of knowledge. In addition to the framework, we developed tools to carry out scenario development, and proposed a language named the lifecycle modeling language (LCML) for the accumulation and exchange of knowledge within this framework. A simple example, scenario development in the selection of cars, showed applicability of LCML as a standardized language for scenario-based LCA.

Further enrichment of LCML and a pattern recognition using such a language is necessary for making scenario development in LCA a more applicable and powerful tool for decision making.

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